

Low-excitation gas in HR 10: possible implications for estimates of metal-rich H_2 mass at high redshifts

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ABSTRACT

We examine the physical conditions of the molecular gas in the extremely red object (ERO), HR 10 (J164502+4626.4, or [HR94] 10) at $z = 1.44$, as constrained by the recent detection of CO $J + 1 \rightarrow J$, $J = 1, 4$ lines. The line ratios of such widely spaced CO transitions are very sensitive probes of gas excitation; in the case of HR 10, they provide a rare opportunity to study the state of H_2 gas in a gas-rich starburst at a cosmologically significant distance. Contrary to earlier claims, we find the CO $J = 5 - 4$ transition to be of low excitation with a brightness temperature ratio of $(5 - 4)/(2 - 1) \sim 0.16$. Depending upon how often such conditions prevail in intense starbursts, this may have serious consequences for molecular gas mass estimates and the detectability of high- J CO lines from similar objects at high redshifts ($z \gtrsim 3$).

Subject headings: galaxies: evolution — galaxies: individual (HR 10) — galaxies: ISM — galaxies: starburst — infrared: galaxies

1. Introduction

A defining characteristic of highly obscured active galactic nuclei and star-forming galaxies is their red optical/infrared (IR) colours. The first few EROs (usually defined such that $R - K > 6$ or $I - K > 5$) were found soon after the advent of near-IR array detectors (Elston, Rieke & Rieke 1988) but were viewed as little more than curiosities. It has become clear,

however, that while EROs provide a negligible contribution to the optical extragalactic background, they may host power sources which dominate the background at other wavelengths, in particular in the submillimetre (submm) and hard X-ray wavebands.

Recent work suggests that EROs form a bi-modal population: a large fraction, possibly around half at $K > 20$, can be identified with obscured starbursts (e.g., Dey et al. 1999); the remainder represent the end products of these starbursts — massive ellipticals at $z \sim 1$ –2 (e.g., Dunlop et al. 1996) whose colours are due to their evolved stellar populations.

Submm surveys with SCUBA (Holland et al. 1999) have demonstrated that a large fraction of the extragalactic submm background originates in ultra-luminous IR galaxies (ULIRGs, $L_{\text{FIR}} \gtrsim 10^{12} L_{\odot}$) at high redshifts (Smail, Ivison & Blain 1997), a population which provides well below 1 per cent of the local luminosity density and which must have evolved dramatically, having provided closer to half of the total background at earlier times. Like the local examples of ULIRGs, many submm sources are distant, gas-rich mergers, the probable progenitors of luminous present-day ellipticals (Ivison et al. 1998, 2000; Smail et al. 1998, 2000; Frayer et al. 1998, 1999; Eales et al. 1999). Unsurprisingly, given the bi-modal population discussed earlier, several have been identified with EROs (Smail et al. 1999). Submm data, in fact, have proved to be an ideal discriminant between the obscured starburst and old elliptical EROs (Dey et al. 1999).

HR 10, an optical/IR-selected galaxy at $z = 1.44$ (Hu & Ridgway 1994; Graham & Dey 1996), was the first ERO to be detected at submm wavelengths (Cimatti et al. 1998; Dey et al. 1999) and to be thus revealed unequivocally as an extremely luminous, dust-obscured starburst ($L_{\text{FIR}} \sim 10^{12} L_{\odot}$), a fact that would have been difficult to surmise from its non-descript optical/near-IR appearance (Dey et al. 1999).

The proper estimation of molecular gas mass in such gas-rich, IR-luminous objects is of central importance since the gas fuels their often enormous ($\sim 10^3 M_{\odot} \text{ yr}^{-1}$) star-formation rates (e.g., Solomon et al. 1992; Dunlop et al. 1994; Rowan-Robinson 2000 and references therein). Comparing $M(\text{H}_2)$ with the dynamical mass allows the determination of the evolutionary status of a galaxy, while a comparison of its dynamical mass with that of a present-day spiral or elliptical can point towards its possible descendent at the current epoch. Finally, since a dust-mass estimate is often available, the resulting gas-to-dust ratio is a significant indicator of the metal enrichment and chemical evolution of galaxies in the early Universe (e.g., Frayer & Brown 1997).

In this paper we examine the physical conditions of the molecular gas in the ERO, HR 10 at $z = 1.44$, and their effect on H_2 mass estimates. Finally, to the extent that such conditions are frequently encountered in starburst environments, there may be far-reaching

consequences for the detection and interpretation of high- J CO lines emitted from starbursts at high redshifts — for the prioritisation of observing bands and receivers for the Atacama Large Millimetre Array (ALMA), for example. Throughout this work, we adopt $q_o = 0.5$ and $H_o = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Physical properties of H_2 in HR 10

The detection of the two widely spaced CO transitions in HR 10 ($J = 2 - 1$, $J = 5 - 4$, Andreani et al. 2000) offers a unique opportunity to examine the physical conditions of the molecular gas using the excitation-sensitive ratio of their brightness temperatures. This is a rare occurrence for high-redshift objects ($z \gtrsim 1$) since it requires a fortuitous combination of redshift and available receivers. For low-redshift objects ($z \lesssim 0.1$), systematic studies of this sort are hindered by large atmospheric attenuation and low antenna efficiencies for frequencies $\nu > 400 \text{ GHz}$, where the CO $J + 1 \rightarrow J$, $J + 1 > 3$ transitions lie and, until the commissioning of a new generation of wide-band heterodyne receivers, by the bandwidth and sensitivity limitations of available instrumentation.

The detection of the CO $J = 2 - 1$ transition is particularly important since, together with CO $J = 1 - 0$, is the most widely studied molecular line in the local Universe. The critical densities of CO $J = 1 - 0$ and $J = 2 - 1$ (i.e. the densities at which the collisional rate out of the upper level and its radiative de-excitation become equal) are $n_{\text{crit}} \sim 2.4 \times 10^2 - 2.4 \times 10^3 \text{ cm}^{-3}$ (for $T_k = 100 \text{ K}$; see e.g. Kamp & van Zadelhoff 2001), and $\Delta E/k \sim 5 - 10 \text{ K}$. These minimal excitation requirements allows these transitions to trace the bulk of the metal-enriched molecular gas and there are several surveys measuring their relative strengths for a wide variety of environments (e.g., Braine & Combes 1992; Hasegawa 1997; Papadopoulos & Seaquist 1998).

The CO $J + 1 \rightarrow J$ line luminosity in units of $\text{K km s}^{-1} \text{ pc}^2$ is given by

$$L_{\text{CO}}(J + 1 \rightarrow J) = \frac{c^2}{2 k \nu_{J+1,J}^2} \left[\frac{D_L^2}{1 + z} \right] \int_{\Delta v} S_{\nu_{\text{obs}}} dv, \quad (1)$$

where $D_L = 2 c H_o^{-1}(1 + z - \sqrt{1 + z})$ is the luminosity distance, and $\nu_{J+1,J}$, $S_{\nu_{\text{obs}}}$, are the rest-frame frequency and the observed flux density of the CO $J + 1 \rightarrow J$ transition (see, e.g., Ivison et al. 1996).

Andreani et al. (2000) have reported almost equal velocity-integrated flux densities for the $J = 5 - 4$ and $J = 2 - 1$ transitions, hence the area/velocity-integrated brightness temperature ratio will simply be

$$\frac{L_{\text{CO}}(5-4)}{L_{\text{CO}}(2-1)} \sim \left(\frac{\nu_{21}}{\nu_{54}} \right)^2 = \left(\frac{2}{5} \right)^2 = 0.16 \quad (2)$$

which is ~ 4 times lower than their reported value and indicates the low excitation of the CO $J = 5 - 4$ line. The new value is bracketed by the global value of ~ 0.07 for the Milky Way, as derived from *Cosmic Background Explorer* measurements (Wright et al. 1991), and $\sim 0.35 - 1$ expected for the conditions in the inner ~ 500 pc of the archetypal starburst M 82 (using data from Seaquist & Frayer 2000; Mao et al. 2000 and references therein).

The surprising fact is not that the aforementioned line ratio is higher for the starburst environment of HR 10 than for the quiescent one of the Milky Way but that it is at least a factor of ~ 2 lower than in the prototype starburst galaxy, M 82. The case of HR 10 shows that very different excitation conditions may indeed prevail in such systems. It is worth noting that such low $(5-4)/(2-1)$ ratios are associated with the low-excitation gas phase present in M 82 (e.g., Mao et al. 2000 and references therein), suggesting that this phase is dominant in HR 10.

The estimate of H_2 mass in the Galaxy and other galaxies utilises the bright CO $J = 1 - 0$ emission and the so-called Galactic conversion factor, X_{CO} (e.g., Young & Scoville 1982, 1991; Bloemen 1985; Dickman, Snell & Schloerb 1986; Bryant & Scoville 1996). For an observed CO $J + 1 \rightarrow J$ line, the H_2 mass is then given by

$$M(\text{H}_2) = X_{\text{CO}} R_{J+1,J}^{-1} L_{\text{CO}}(J+1, J) \quad (3)$$

where $R_{J+1,J}$ is ratio of the CO $J + 1 \rightarrow J$ and $J = 1 - 0$ line luminosities.

The range of R_{21} observed in a variety of Galactic and extragalactic environments is $\sim 0.5 - 1$ (e.g., Braine & Combes 1992; Hasegawa 1997; Papadopoulos & Seaquist 1998) hence the expected range of R_{54} for HR 10 is $\sim 0.08 - 0.16$ (see Equation 2), significantly lower than ~ 1 , the value for an optically thick and thermalized line.

Unlike strongly lensed objects, where differential lensing may bias the dust continuum and line ratios towards a warmer dust/gas component (Blain 1999; Papadopoulos et al. 2000), the lack of strong gravitational lensing in HR 10 (Dey et al. 1999) allows a more straightforward interpretation of the observed line ratio. In the absence of more data, we examine the physical conditions compatible with the observed $(5-4)/(2-1)$ line ratio assuming a single gas phase and using a large-velocity gradient (LVG) code (e.g., Richardson 1985). The code was run for the typical range of temperatures $T_{\text{kin}} = 30 - 60$ K that characterise the warm-dust component (where the bright CO emission also arises) in IR-bright galaxies (e.g. Devereux & Young 1990 and references therein). A typical solution is $T_{\text{kin}} = 45$ K and $n(\text{H}_2) = 10^3 \text{ cm}^{-3}$ ($T_{\text{dust}} \sim 40$ K, Dey et al. 1999). Such a diffuse, low-excitation gas phase

with such temperatures is not unusual in extreme starburst systems (Downes & Solomon 1998); it is present (but not dominant) in much less luminous starbursts like M 82 (Hughes, Gear, & Robson 1994; Mao et al. 2000) and is probably the product of their UV-intense and kinematically violent environments (Aalto et al. 1995).

For these conditions $R_{54} \sim 0.14$, while higher transitions have $R_{65} \sim 0.035$ and $R_{J+1,J} \lesssim 5 \times 10^{-3}$ for $J + 1 > 6$. The low excitation of the $J = 5 - 4$ line in particular is due to the low density rather than temperature since, for optically thick and thermalized gas, such a low ratio implies $T_{\text{kin}} < 10 \text{ K}$, much lower than the observed dust temperature. The claim by Andreani et al. that T_{kin} is usually significantly less than T_{dust} is not valid; usually they are similar, except for the photodissociation regions (PDRs) in the surfaces of UV-illuminated molecular clouds where $T_{\text{kin}} > T_{\text{dust}}$ (e.g., Hollenbach & Tielens 1999). Here we must stress that all other LVG solutions compatible with the low $(5-4)/(2-1)$ ratio result to $R_{J+1,J} \lesssim 0.05$ for $J + 1 \geq 6$.

3. Consequences for high-redshift galaxies

At high redshifts ($z \gtrsim 3$), the usual instruments of choice for detecting CO lines are millimetre-wave interferometers. These are only capable of accessing high- J (i.e. $J > 2$) CO $J + 1 \rightarrow J$ lines. In such cases, the obvious consequence of the low excitation of such lines is that they become difficult to detect, even if there is a large quantity of molecular gas. Equivalently, any H_2 mass estimates based on the assumption of optically thick and thermalized high- J CO lines (e.g., Evans et al. 1996; van Ojik et al. 1997) may underestimate the mass present, or its upper limit, by a large factor ($\gtrsim 10$).

In the case of HR 10, scaling its CO $J = 5 - 4$ flux to $z = 4$ (reasonably typical for the large samples of quasars, radio galaxies, Lyman-break and submm-selected galaxies that are now being assembled – e.g., Steidel et al. 1999; Smail et al. 2000) yields a velocity-integrated flux density of $\sim 0.8 \text{ Jy km s}^{-1}$ (from Equation 1), received at $\nu_{\text{obs}} \sim 115 \text{ GHz}$. This is a rather weak signal. While still detectable in a dedicated observing run of a few tens of hours with a sensitive present-day millimetre-wave interferometer, it would evade detection in a typical survey for such lines in full samples of high-redshift galaxies (e.g., van Ojik et al. 1997). Moreover, an estimate of $M(\text{H}_2)$ based on the CO $J = 5 - 4$ line only, and the assumption that it is optically thick and thermalized, would yield a value $\sim 6 - 12$ times too low (Equation 3, $R_{54} \sim 0.08 - 0.16$). The previous simple excitation analysis suggests that CO $J + 1 \rightarrow J$ (with $J + 1 \geq 5$) lines can be poor global mass tracers in such environments, underestimating the H_2 mass by factors of $\gtrsim 10$, depending on the particular line used and the prevailing physical conditions.

For the least excitation-biased mass estimates of metal-enriched molecular gas it is clearly important to observe the lowest two transitions of CO. At high redshifts this is currently possible only in cases where there is a fortuitous combination of redshift and available receivers. Sadly, this precludes a systematic inventory of molecular gas mass at $z \gtrsim 3$ with present instruments, though the Green Bank Telescope, the upgraded Very Large Array (VLA) and ALMA will provide the necessary instantaneous bandwidth (velocity coverage), tuning range (redshift coverage) and sensitivity to detect many CO lines at such redshifts. Fig. 1 demonstrates that several CO line ratios will be available for galaxies at virtually all redshifts, with a small gap at $z \sim 2.7 - 3.4$ ($z \sim 2.7 - 4.1$ if one considers only ALMA). For the CO(1–0) and CO(2–1) lines, however, ALMA provides the only coverage at $z \sim 2.0 - 2.7$, a potentially important range for a number of known galaxy populations (Steidel et al. 1999; Ivison et al. 1998, 2000; Smail et al. 2000), and to do this ALMA requires the so-called ‘Band 1’ receivers (31.3–45 GHz).

Currently, the commissioning of a new generation of sensitive receivers with wider tuning ranges on mm/sub-mm telescopes around the world will enable the extension of multi-line studies of nearby starbursts ($L_{\text{FIR}} \sim 10^9 - 10^{10} L_{\odot}$) towards more luminous systems ($L_{\text{FIR}} \sim 10^{11} - 10^{12} L_{\odot}$) at larger distances. This will reveal whether a low-excitation gas phase dominating the emission of the ^{12}CO rotational lines is indeed more frequently encountered at higher FIR luminosities and will yield a firm assessment of the expected luminosities of higher- J lines in luminous starbursts found at high redshift.

4. Conclusions

We have presented a brief analysis of the physical conditions of molecular gas in the $z = 1.44$ extremely red object, HR 10, using the CO $J = 2 - 1$, $J = 5 - 4$ lines. HR 10 provides a rare opportunity to investigate low- J and high- J CO lines in an intense starburst at a cosmologically significant distance. Its case can thus be instructive for similar environments in objects at still higher redshifts. Our conclusions are as follows:

- Contrary to earlier claims, we find the CO $J = 5 - 4$ line to be of low excitation, with a brightness temperature ratio of $(5 - 4)/(2 - 1) \sim 0.16$, likely due to low densities rather than low temperatures.
- The CO $J + 1 \rightarrow J$, $J + 1 \geq 5$ emission lines from similar galaxies at $z \gtrsim 3$ would be hard to detect using current millimeter-wave arrays. If detected, the usual assumption made for their excitation, namely that they are thermalized and optically thick, may underestimate H_2 gas masses by a factor $\gtrsim 10$.

This analysis may have some bearing on the relative priority given to the so-called ‘Band 1’ frequencies/receivers (31.3–45 GHz) for ALMA. It is at these frequencies that one would detect the lowest-excitation CO $J = 1 - 0$ transition from a substantial fraction of the submm-selected galaxy population (‘SCUBA galaxies’), systems which appear to have a median redshift of 2.5–3 (Smail et al. 2000). The upgraded VLA may also have a significant role to play; it will have a similar *effective* aperture to ALMA at those frequencies, but the expected phase stability at Atacama and the $2\times$ larger field of view means that ALMA is likely to be the interferometer of choice.

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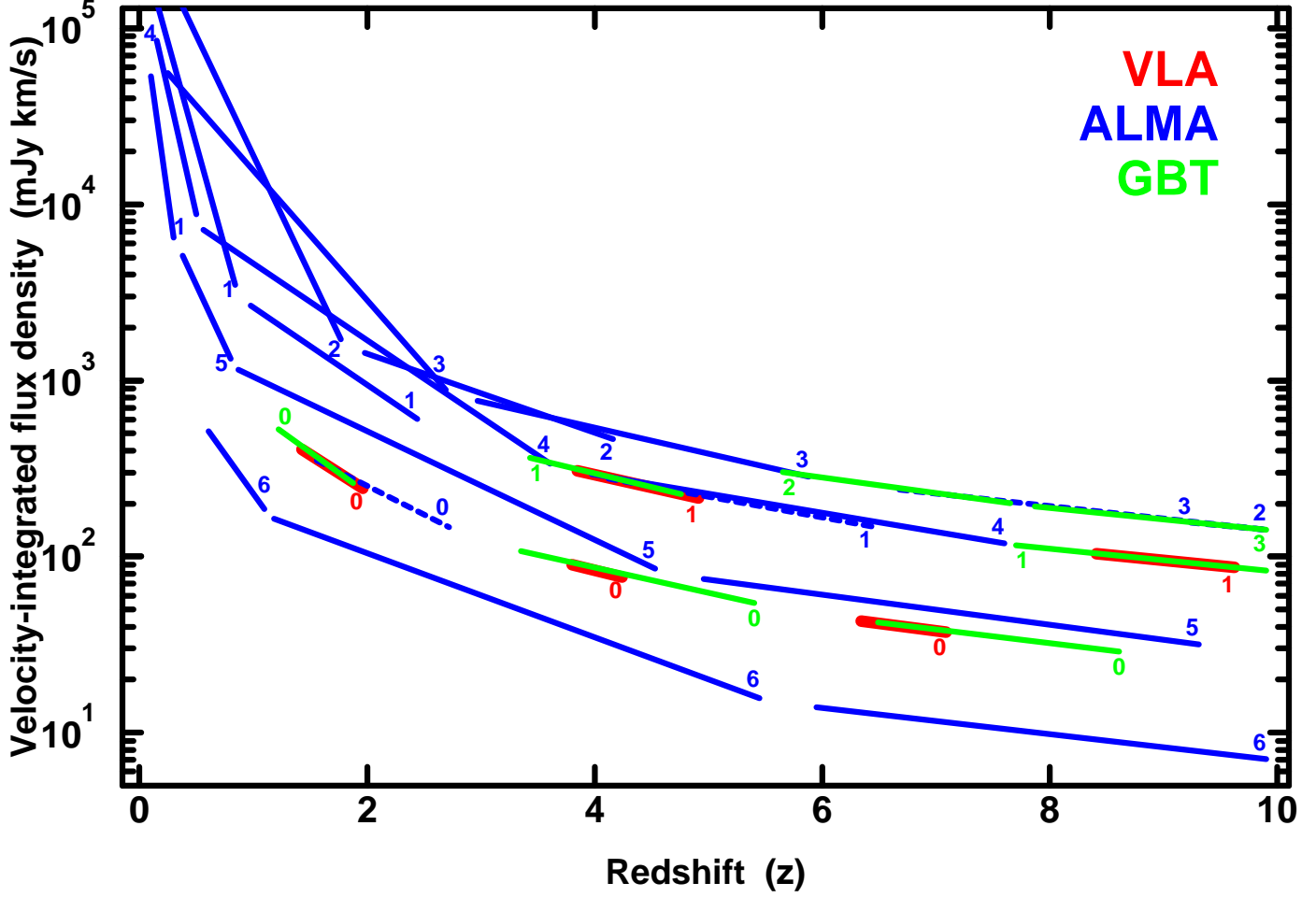


Fig. 1.— The expected velocity-integrated flux density, $\int S_{\nu_{\text{obs}}}(J+1, J) dV$, (J is labeled, $J = 0 - 6$) emitted by $10^{11} M_{\odot}$ of metal-enriched H_2 gas ($Z/Z_{\odot} = 1$) with properties identical to those of HR10. Each line represents the velocity-integrated flux density appropriate for the redshifts where each $J+1 \rightarrow J$ transition is available to the receivers at a particular telescope. For the VLA, the bands are taken to be the regions where current receivers have at least 50 per cent of their optimum sensitivity (Perley 2000). Plans for the Extended VLA include continuous frequency coverage from 1.1 to 50 GHz, which will provide coverage of low- J CO transitions at $z \geq 1.3$. For ALMA, the definitions of ‘Bands 1–10’ were taken from the ALMA Construction Project Book (www.tuc.nrao.edu/~demerson/almapbk/construc/cons_toc.htm), and Band 1 coverage is shown by dashed lines; for the GBT, the bands were taken from the Short Guide to the Green Bank Telescope (www.nrao.edu/GBT/proposals/short_guide.html).